

# Effects of fire disturbance on forest hydrology

YAO Shu-ren

(Nanjing Forestry Police College, Nanjing 210041, P. R. China)

**Abstract:** Fire is quite a common natural phenomenon closely related to forest hydrology in forest ecosystem. The influence of fire on water is indirectly manifested in that the post fire changes of vegetation, ground cover, soil and environment affect water cycle, water quality and aquatic lives. The effect varies depending upon fire severity and frequency. Light wildland fires or prescribed burnings do not affect hydrology regime significantly but frequent burnings or intense fires can cause changes in hydrology regime similar to that caused clear cutting.

**Keywords:** Forest fire, Forest hydrology, Water cycle, Flow, Water quality

**CLC number:** S762; S716

**Document code:** B

**Article ID:** 1007-662X(2003) 04-0331-04

Forest fires are quite common in nature. Some forest types exit just due to the fact that fires kill their competitors. The influence of fire on water is indirectly manifested in that the post fire changes of vegetation, ground cover, soil and environment affect water cycle, water quality and aquatic lives. Fires occur frequently in some ecosystems destroying trees and affecting surface hydroprocesses. The effect varies depending upon fire severity and frequency. Crown fires destroy tree canopy that can intercept rain and evaporation. Surface fires can reduce soil infiltration and increase surface runoff and other sediments. The effect of fire on water quality depends on fire frequency, severity, site conditions, post fire weather and reforestation rate. Light wildland fires or prescribed burnings do not affect hydrology regime significantly but frequent burnings or intense fires can cause changes in hydrology regime similar to that caused clear cutting. The research on hydrological effects of fire once was reviewed by Tiedemann *et al.* (1979), Chandler *et al.* (1983), Wright and Bailey (1982).

## Effects of fire on water cycle

### Interception

The interception of tree canopy and ground cover is important in reducing the impact of water drop on soil, surface runoff and erosion, and in increasing infiltration. The intercepted water by tree leaves can be 150% of the dry mass of the leaves. Many forest shrubs can intercept 1-2 mm water (Green 1981). The interception of vegetation depends on rain intensity, duration and ratio of surface area to volume. The greater the intensity, the longer the duration is and the smaller the ratio of surface area to volume, the less the interception is. When rainfall is 10 mm, the interception by broadleaved canopy can be 20-30% of the rain and that

by coniferous canopy can be 50%. The destruction of canopy post fire, especially that of ground cover causes dramatically reduction of interception.

### Infiltration

The factors affecting infiltration are vegetation canopy, ground cover, soil type, soil organic matter and soil structure. Canopy and ground cover intercept rainfall at one hand and absorb water at another hand, which prolong the infiltration time. The disappearing of interception post fire and destruction of soil structure reduce the soil infiltration and increase surface runoff. Literature reported (Horton, 1955) that infiltration post fire is only one third of that prefire in oak forest in Illinois, USA. The occurrence of water resistant layer also contributes to the reduction.

### Water holding

Water holding capacity of forest land mainly depends on thickness of organic layer and decomposition state. Water hold by newly fallen leaf is 150 % of its dry mass and for humus it is 500%. Conifer needles of 1-cm thick can hold 0.5 mm rainfall. The water loss can be 5 mm rainfall if litter of 10 cm is burned off (Kozolowski 1974). The water holding loss of humus is ten times that of litter. Ground coverage have strong influence on soil water holding capacity. The destruction on litter and humus can severely lower water holding of surface soil. But some research indicated that the reduction of evaporation post fire can cause higher moisture content of soil than pre-burning. The moisture of soil in a plot of forest in Oregon State, USA, increased by 12.7 cm after fire. It was concluded after 3 years of successive observation that it would take 5 years for the forest to recover to the pre fire level (Chandler1983).

### Snow accumulation and melting

Snow accumulation in forest is affected by stand density, terrain (aspect, slope) and elevation. Moderate closure, mild north faced slope and high elevation are most favorable for snow accumulation. The effect of fire on snow ac-

cumulation mainly depends on fire intensity and area burned. High intensity fires with small area burned can increase snow accumulation because the cluster of dead trees provides space for snow accumulation. Low intensity fires with large area burned can also increase snow accumulation due to the increase space created by partially burn dead trees. Low intensity fires with small area burned have little influence on snow accumulation, while high intensity fires can reduce snow accumulation since the open land post fire with higher wind speed is unfavorable for snow accumulation. The effect of fire on snow is similar to that of cutting. Selective cutting, belt cutting and gradual cutting can increase snow accumulation ranging from 0-50% and averaged 25%. The effect of belt cutting and selective cutting is quite significant. The remnants on burned site are mostly black matters (charcoal, ash and blackened trunks), which can absorb large amount of solar long wave radiation and thus increase soil temperature, cause snow melting earlier.

### Runoff

Surface runoff without burning is less than 1% of rainfall in broadleaved brush but can be 10%-15% and the highest of 40% of the rainfall in the first year post fire (Helvey 1980; Zheng, 1990). The snow melting and runoff at burning site is 8 times as that without burning in west Montana State USA. The surface runoff at burning site maximized at the first year. The effect of prescribed burning on runoff depends on slope. No more runoff occurs at 1%-4% slope. Runoff may continue for 12-18 months for 8%-20% slope and 31 months for slope of 37%-60% (Wright 1982).

### Landslide

Landslide happens post fire because of declination of soil infiltration capacity and loss of holding effect of vegetation roots on soil. Another soil erosion similar to landslide is mud flow which is the phenomenon that soil and rainfall run down together under the impact of rain (commonly storm) when vegetation and ground cover are burned off. Generally speaking, seldom landslide or mud flow occur shortly after fire because the root system is not totally destroyed with some holding capacity remained. However several years later when the root system decays, landslide and mud flow can be more severe.

### Effects of fire on flow and deposit

Effects of fire on down stream water are mainly shown in two aspects: increasing river flow and degrading water quality. The area burned, fire intensity, soil type, river size and geographical location all have influence on river deposit and flow.

#### River deposit

The destruction of forest vegetation post fire degrades the hydrological function of the forests and increases sur-

face runoff, thus increasing sand deposit and water flow in river. The increase of flow also accelerates flow velocity and increase impact of flow on riverbanks, which result in more deposit. Sometimes the deposits are more than that from surface erosion. It is estimated that the deposit in eastern Washington one year after fire could be 41-127 m<sup>3</sup> while no deposit occurred before burning. The relationship between sand deposit and area burned is exponential, i.e., the deposit of a 100-hm<sup>2</sup> fire in size is 10 000 times of that of a 10-hm<sup>2</sup> fire (Bond1996).

### River flow

The degradation of vegetation interception and transpiration and ground cover absorption leads to more water infiltrate into soil. Post forest fire, surface runoff increase, and snow melt earlier, which result in the following effects on down stream rivers:

Annual river flow increases by 60% as the maximum.

River flow increase not more than 20% in dry season.

Flood comes earlier and more severe.

Storm and flood occur more frequently.

Diurnal variation of river flow decreases.

Intermittent river flow keep running.

The flow of downstream river increase significantly after fire, especially post large fire. Results from Arizona shows that the water flow in the first year after fire is 10 times that before fire and formerly intermittent river becomes continuous river (except for extreme dry years). The amount of storm and flood shows an increase after fire, too. The storm in a broadleaved brush catchment in California increased by 3-5 times after fire, with the flow of the first storm 4 times of the predicted value. The flood post fire is 2-45 times higher than that before fire. It will take 30-70 years to come back to normal level (Whitmore 1975).

Any disturbance causing changes in forest density, structure and composition will lead to significant change in hydrobalance. The increase of total water yield of catchment affected by severe fire is similar to that of clear cutting site. It is positively proportional to the percentage of burned forest. If the litter and organic layer are severely burned out, the effect on flood will be significant. It has been observed that even slash burning could also increase surface runoff and erosion and severe fire increase the deposit dramatically (Cai *et al.* 1995).

### Effects of fire on downstream water quality

The literature is replete with evidence of fire-induced changes in water quality, including increased sedimentation and turbidity, increased stream temperatures, and increased concentrations of nutrients resulting from surface runoff (Buckhouse and Gifford 1976; Feller and Kimmins 1984; Richter and Ralston 1982; Striffler and Mogren 1971; Tiedemann *et al.* 1979). All the changes caused by fire such as runoff, soil erosion, drought erosion and shift of river can affect downstream water quality to some extent

(Robinson & Minshall 1986; Britton 1990; Beaty 1994). Turbidity is an important index for water quality. The turbidity of downstream shows increase after fire. The average turbidity of rivers in north California is 470-2000  $\mu\text{g/g}$ . Cutting can increase turbidity by 8 times. Slope is main factor determining the effect of fire on downstream turbidity. No significant change occurs for slope of 1%-4%. Turbidity increases by 1.5 times for slope of 8%-20% and by 5 times for slope of 37%-61%. The deposit mainly comes from banks and surface soil. Data from California (Su *et al.* 1998) showed that 74% of the deposit came from banks and 22% from surface runoff, only a few from wind erosion and landslide.

The effects of fire on downstream water quality can also be found in water chemical component, especially for N, P, K, Ca, Mg and Na. The nitrogen in water is in three forms: nitrated N, ammoniated N and organic N. Data from Tideman showed that the nitrogen in river was 0.005  $\mu\text{g/g}$  for small flow and 0.016  $\mu\text{g/g}$  for large flow before fire. They were 100 times post fire. This indicated that great nitrogen loss occurred in burning site. Although this could not cause severe damage, effects still exist.

Phosphorus exists in soil solution, rivers and lakes in the forms of either inorganic or organic states. Total phosphorus increases after burning. Tideman's data showed that the total phosphorus in river after fire was 2 to 3 times of that before fire, but the increase would not cause changes in water quality. Some studies showed that fire did not affect total phosphorus in river. Hydrocarbonic acid anion is the major anion in water. Many studies showed that the hydrocarbonate either in soil or in downstream river increases.

The effects of fire on cation in downstream river vary with studies. For some cases, the results might be contradictory. Results from a study conducted in a region in California showed that no changes occurred in cation contents of river after forest fire. This was explained by the fact that for the acid soil, cations leached were absorbed anions in soil instead of leaching into river. The  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  in downstream river are higher than that in upper reaches of the river. This might have some relations with the strong winds or intense rainfall after burning, which blow or carry ash into river. Some studies revealed that major cations in river were negatively proportional to river flow. This might be caused by the increase of runoff might dilute the river.

The latest research of fire on water quality of streams was made by Minshall *et al.* (2001) showed that some immediate impacts such as damaged moss in headwater streams (e.g. Char Creek), minor increases in sedimentation (e.g. Little Loon Creek), and increases in concentrations of most chemical factors measured. However, in general, no major adverse effects on lotic communities were evident in the months immediately following the fire. Increased concentrations of dissolved chemicals in stream water in burned watersheds are consistent with most other studies of wildfire (Tiedemann *et al.* 1978; Schindler *et al.*

1980; Britton 1991), although a few studies have shown no effect under special circumstances (e.g. Johnson and Needham 1966; McColl and Grigal 1977). In the present study, the increases in many of the ions, including the nutrients nitrogen and phosphorus, were not exceptionally large and the relative concentrations remained fairly constant and, as in other studies (Tiedemann *et al.* 1978; Schindler *et al.* 1980; Gluns and Toews 1989), did not exceed the water quality criteria established. Except for Char Creek, water temperatures probably had a little increased if at all as a direct result of the fire. For example, an increase of less than 1°C was recorded in a small (ca. 3 L/s) stream in central Washington during a fire (Berndt 1971). If adverse temperature increases had occurred, we would have expected to have seen greater impacts on the periphyton and macroinvertebrates in the October 1979 samples than were found. The adverse effects of fire on the biotic community were particularly evident from the July 1980 samples. These effects were largely caused by physical changes of the stream, such as major channel cutting and sediment scouring, resulting from enhanced spring snowmelt runoff or summer precipitation, rather than from chemical or thermal changes. Increased runoff in the burn streams exported nutrients, altered the substratum, removed organic matter and periphyton, and changed the species/abundance relationships of the benthic macroinvertebrate assemblage. These impacts were accentuated by the steep terrain in which our study sites occurred and by the slow recovery of terrestrial vegetation after the fire. The fire also increased the sensitivity of the burn streams to smaller-scale disturbances, such as thunderstorms, which had major impacts on the burn streams but not on the reference streams. Finally, even in the first year, there was a high degree of variability in the effects of the fire among the various streams as a result of differences in snowmelt patterns and precipitation.

### Effects of fire on aquatic life

Severe fires can accelerate erosion and sediment when heavy rain follows fire or in drought regions where it will take a few years for vegetation to recover. The direct exposure to solar radiation can cause change in river temperature with extent similar to that caused by clear cutting. Data from a river in Oregon showed that the water temperature increased 6.7-7.8 °C. In summer the water temperature can increase 12.2 °C with the maximum increase of 21°C. The temperature increase causes changes in habitat thus further influence aquatic lives, especially for some fishes. Literature (Wyk 1978) reported that no significant change of number and species of large invertebrates occurred in rivers of Alaska post fire. Related research can be seen from the literature (Albin, 1979; Minshall, 1990; Minshall & Brock, 1991; Richards & Minshall, 1992; Robinson *et al.*, 1994; Minshall *et al.*, 1995; Roby & Azuma 1995; Rinne 1996).

The latest work by Minshall *et al.* (2001) showed that the taxa richness and total abundance tended to be lower in burn than in reference streams but to converge near the end of the study. Increases in the final years in both burn and reference streams were associated with reduced flows due to drought. Total biomass and that of the scraper, filterer and miner functional groups usually were greater in the burn streams. Many other taxa showed the opposite response. The adverse effects of wildfire on the biotic community were largely the result of physical changes in habitat due to increased runoff.

## References

- Albin, D.P. 1979. Fire and stream ecology in some Yellowstone Lake tributaries [J]. *California Fish Game*, **65**: 216-238.
- Beaty, K.G. 1994. Sediment transport in a small stream following two successive forest fires [J]. *Canadian Journal of Fisheries and Aquatic Sciences*, **51**: 2723-2733.
- Berndt, H.W. 1971. Early effects of forest fire on streamflow characteristics [R]. U. S. Forest Service Research Note PNW-148.
- Bond, J., Wilgen B.W. 1996. Fire and plants [M]. London: Chapman & Hall, 156-159.
- Britton, D.L. 1990. Fire and the dynamics of allochthonous detritus in a South African mountain stream [J]. *Freshwater Biology*, **24**: 347-360.
- Britton, D.L. 1991. Fire and the chemistry of a South African mountain stream [J]. *Hydrobiologia*, **218**, 177-192.
- Buckhouse, John, C. and Gerald, F. Gifford. 1976. Grazing and debris burning on pinyon-juniper sites -- Some chemical water quality implications [J]. *J. Range Manage*, **29**: 299-301.
- Cai, T.J., Feng, Z. X. 1995. Study on effects of fire on river flow [J]. *Forest Science*, **15**(2).
- Chandler, Craig, Phillip Cheney, Philip Thomas, Louis Trabaud, and Dave Williams. 1983. Fire in forestry, Volume I: Forest fire behavior and effects [M]. New York: John Wiley & Sons, 450 p.
- Chandler. 1983. Fire in Forestry [M]. New York: Wiley & Sons, Vol.1~3.
- Feller, M.C. and Kimmins, J.P. 1984. Effects of clearcutting and slash burning on streamwater chemistry and watershed nutrient budgets in southwestern British Columbia [J]. *Water Resource. Research*. **20**: 29-40.
- Wayne Minshall, G., James, T., Brock, B., Douglas, A., Andrews, C., and Christopher, T., Robinson, D. 2001. Water quality, substratum and biotic responses of five central Idaho (USA) streams during the first year following the Mortar Creek fire [J]. *International Journal of Wildland Fire*, **10**: 185-199.
- Helvey, J.D. 1980. Effects of a north central Washington wildfire on runoff and sediment production [J]. *Water Resources Bulletin*, **16**: 627-634.
- Horton, 1955. Development of vegetation after fire in the chamise chaparral of Southern California [J]. *Ecology*, **36**: 244-262.
- Johnson, C.M., Needham, P.R. 1966. Ionic composition of Sagehen Creek, California, following an adjacent fire [J]. *Ecology* **47**: 636-639.
- Kozolowski, T.T. 1974. Fire and ecosystems [M]. New York. Academic Press, 542-544.
- McColl, J.G., Grigal, D.F. 1977. Nutrient changes following a forest wildfire in Minnesota: effects in watersheds with differing soils [J]. *Oikos*, **28**: 105-112.
- Minshall G W 1990. Changes in the stream/riparian environment following the Mortar Creek Fire in central Idaho [J]. *Bulletin of the Ecological Society of America*, **71**:
- Minshall G W, Brock. 1991. Observed and anticipated effects forest fire on Yellowstone stream ecosystems [C]. In: R.B. Keteer and M.S. Boyce (eds), *The Greater Yellowstone Ecosystem: Balancing man and nature on America's wildlands*. New Haven: Yale University Press, 146-157.
- Minshall, G.W., Robinson, C.T., Lawrence, D.E., Andres, D.A., Brock, J.T. 2001. Benthic macroinvertebrate assemblages in five central Idaho (USA) streams over a 10-year period following disturbance by wildfire [J]. *International Journal of Wildland Fire*, **10**: 201-213.
- Minshall, G.W., Robinson, C.T., Royer, T.V., Rushforth, Sr. 1995. Benthic community structure in two adjacent streams in Yellowstone National Park five year after the 1988 wildfires [J]. *Grea Basin Naturalist*, **55**: 193-200.
- Richads, C., Minshall, G.W. 1992. Spatial and temporal trends in stream macroinvertebrate communities: the influence of catchment disturbance [J]. *Hydrobiologia*, **241**: 173-184.
- Richter, D.D. and Ralston, C. W. 1982. Prescribed fire: Effects on water quality and forest nutrient cycling [J]. *Science* **215**(4533): 661-663.
- Rinne, J.N. 1996. Short term effects of wild fire on fishes and aquatic macroinvertebrates in the Southwestern United States [J]. *North American Journal of Fisheries management*, **16**: 653-658.
- Robinson, C.T., Minshall, G.W. 1986. Effects of disturbance frequency on stream benthic community structure in relation to canopy cover and season [J]. *Journal of the North American Benthological Society*, **5**: 237-248.
- Robinson, C.T., Rushforth, Sr., Minshall, G.W. 1994. Diatom assemblages of streams influenced by wildfire [J]. *Journal of Phycology*, **30**: 20-216.
- Roby, K.B., Azuma, D.L. 1995. Changes in a reach of a northern California stream following wildfire [J]. *Environmental Management*, **19**: 591-600.
- Schindler, D.W., Newbury, R.W., Beaty, K.G., Prokopowich, J., Ruszczyński, T., Dalton, J.A. 1980. Effects of a windstorm and forest fire on chemical losses from forested watersheds and on the quality of receiving streams [J]. *Canadian Journal of Fisheries and Aquatic Sciences*, **37**: 328-334.
- Striffler, W.D. and Mogren, E.W. 1971. Erosion, soil properties, and revegetation following a severe burn in the Colorado Rockies [C], p. 25-36. IN C. W. Slaughter, Richard J. Barney, and G. M. Hanson (eds.). *Fire in the northern environment - A symposium*. USDA, For. Serv. Pacif. Northw. For. and Range Exp. Sta., Portland, OR.
- Su, L.F., Tian, X.R. 1998. Research and application of prescribed burning [J]. *Fire Science*, **7**(3): 61-67.
- Tiedemann, A.R., Conrad, C.E., Dieterich, J.H., Hombeck, J.W., Megahan, W.F., Viereck, L.A., Wade, D.D. 1979. Effects of fire on water: a state-of-knowledge review [R]. USDA Forest Service General Technical Report WO-10.
- Tiedemann, A.R., Helvey, J.D., Anderson, T.D. 1978. Stream chemistry and watershed nutrient economy following wildfire and fertilization in Eastern Washington. *Journal of Environmental Quality*, **7**: 580-588.
- Tiedemann, Arthur, R., Carol, E. *et al.* 1979. Effects of fire on water: A state-of-knowledge review [R]. USDA, For. Serv. Gen. Tech. Rep. WO-10. Washington, D.C. 28.
- Whitmore, T.C. 1975. Forest and fire of the Far East [M]. Oxford: Clarendon Press, 282-297.
- Wright, A., Bailey, W. 1982. Fire ecology [M]. New York: John Wiley & Sons, 274-289.
- Wright, A. and Bailey, W. 1982. Fire ecology, United States and southern Canada [M]. New York: John Wiley and Sons, Wiley-Interscience Publication, 501 p.
- Wyk, P. Van. Problems of fire in Kruger Park [J]. *African Wild*. 1978, **22**(4): 268-280.
- Zheng, Huanneng. 1990. Effects of fire in ecosystem balance [J]. *Journal of Northeast Forestry University*, **18**(1): 8-12.